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# PROGRESS IN GUIDANCE AND CONTROL RESEARCH FOR SPACE ACCESS AND HYPERSONIC VEHICLES (PREPRINT)

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Over the past decade, both NASA and the U.S. Air Force have directed significant efforts aimed at reducing the cost of access to space as well as improving the reliability and safety of launch vehicles. From a guidance and control perspective, efforts have focused on the development of fault tolerant autonomous systems that can recover vehicles from failures or damage when physically possible. The state of the art is summarized in this manuscript and some of the challenges preventing widespread use of some of the techniques are discussed. The integration of vehicle health management systems with adaptive guidance and control is also discussed.

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# Progress in Guidance and Control Research for Space Access and Hypersonic Vehicles

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## Abstract

*Over the past decade, both NASA and the U.S. Air Force have directed significant efforts aimed at reducing the cost of access to space as well as improving the reliability and safety of launch vehicles. From a guidance and control perspective, efforts have focused on the development of fault tolerant autonomous systems that can recover vehicles from failures or damage when physically possible. The state of the art is summarized in this manuscript and some of the challenges preventing widespread use of some of the techniques are discussed. The integration of vehicle health management systems with adaptive guidance and control is also discussed.*

## 1. INTRODUCTION

Efforts to develop reusable launch vehicles over the past decade have spurred the development of fault tolerant autonomous guidance, control and on-line trajectory reshaping algorithms. The goal of these efforts has been to replace, to the extent possible, the flexibility of the archetype adaptive controller, the human pilot. The early to mid 1990's saw a surge in the development and testing of adaptive and reconfigurable flight control technologies; however, these applications were aimed primarily at manually controlled aircraft. Both direct and indirect adaptive inner-loop flight control approaches have been pursued and flight-tested in recent years. Indirect adaptive control approaches that make use of on-line system identification[1] and receding horizon optimal control [2] have been developed and were flight tested on the VISTA F-16 in 1995. The indirect adaptive approach developed under this project used a static stochastic regularized least squares approach to estimate control derivatives of a damaged aircraft. The most recent estimates of the control derivatives were used to compute a finite time solution to a linear quadratic regulator problem that was applied to the aircraft control inputs. The principal objective of this project was to minimize the impact of failures or damage on the pilot's ability to control the craft and the project was successful in this regard. Direct methods such as [3, 4] have been successfully flight tested on a highly modified F-15 known as NASA 837 [5, 6], the X-36 [7] and JDAM guided munitions [8, 9]. Among the benefits demonstrated have been maintenance of flying qualities in the presence of control effector failures, the ability to compensate for large modeling errors and reduced control design time. Verification and validation (V&V) methods for flight critical systems that make use of these direct methods is still nascent and the manned flight demonstrations to date have relied upon safety of flight monitors that can revert to a safe mode that gives the pilot control of the aircraft using the standard control laws in the event that the research flight control laws cause an unsafe condition. An objective comparison of a number of modern nonlinear and adaptive flight control methods is presented in [10].

For autonomous aerospace vehicles without pilots or remote operators, inner-loop reconfigurable flight control is a necessary component of a fault tolerant flight system; however, it may not be sufficient to recover from failures that significantly reduce the control power available for flight path control or from failures that result in significant perturbations to the aerodynamic forces that normally act on the vehicle. Reconfigurable inner-loop flight control normally deals with maintaining positive control of fast variables such as accelerations or body-axis angular rates. Under failure conditions the ability to maintain nominal control of these variables may or may not exist, or in some cases control may be retained, but at a reduced level of performance. This ability is largely based upon the number and types of effectors available on the craft. In the event that nominal closed inner-loop performance is degraded, adaptation in the outer guidance loops that maintain flight path control may be required. On manually controlled aircraft, the pilot would be responsible for detecting degraded inner-loop flight control performance and responding appropriately by maintaining flight path control at a reduced

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level of performance (e.g. slower speed of response). For autonomous systems, the capabilities of the human operator must be built-in to the guidance,control and trajectory generation system in order to achieve a comparable level of fault tolerance . Guidance adaptation and reconfigurable control may be capable of recovering from failures or damage that do not significantly change the nominal aerodynamic forces on an aircraft; however, when the lift and drag forces change significantly from those acting on the nominal vehicle, trajectory retargeting or reshaping may be required. The effect of lift and drag perturbations resulting from failures or damage are especially important in the unpowered flight phases for reentry vehicles, since these perturbations significantly affect range capabilities. In 2003 an integrated adaptive guidance control and trajectory reshaping algorithm was flight demonstrated using in-flight simulation of the X-40A reentry vehicle [11]. This effort resulted the first flight demonstration of a fault tolerant autonomous landing system and demonstrated the ability of the X-40A to accommodate multiple control surface failures when equipped with this system. More than 75 approaches and landings were completed under this project and extensive non-real time simulations were completed to assess many failures that were not considered in-flight.

Abort planning for ascent has traditionally relied upon extensive ground planning for a finite number of failure scenarios like power-pack-out at specified times. Such planning is time consuming and does not support on-demand spacelift objectives where vehicle configurations and payloads might vary with each mission. It is undesirable to spend months planning abort trajectories for each specific flight. One promising approach that addresses this problem is based on a hybrid analytical/numerical trajectory optimization technique developed in [12]. In [13], the developers apply this approach to the problem of generating abort trajectories for a reusable launch vehicle and demonstrated the ability to rapidly and consistently plan aborts for unforeseen failures. The hybrid analytical/numerical approach starts with an analytic vacuum solution to the ascent problem that ignores the effects of the atmosphere. A numerical algorithm gradually introduces the troublesome atmospheric terms and the problem is iteratively solved until the desire full atmospheric trajectory is computed. While the approach has consistently performed well in non-real-time simulations under a wide range of conditions, there are no convergence guarantees which represents an obstacle to its acceptance for flight critical systems.

Hanson, et.al. [14, 15, 16] at NASA Marshall Space Flight Center documented the results of tests on a variety of different advanced guidance and control techniques designed for the X-33. The algorithms were tested in non-real time high fidelity simulations of the X-33 vehicle. The test battery included stressful conditions such as power-pack-out, control surface failures, as well as dispersions in winds, aerodynamic characteristics and mass properties. The advanced methods were evaluated against the performance of the X-33 baseline guidance and control system in order to ascertain the benefits of the new technologies. A number of entry guidance techniques were tested including Drag-Energy 3D (EAGLE) [17, 18] and Quasi-Equilibrium Glide [19, 20, 21] which tied for the best scores as well as a Linear Quadratic Regulator[22], Predictor-Corrector[23], and Shuttle-like entry[24] guidance method. A number advanced control methods were developed and tested under this project as well including a dynamic inversion based adaptive/reconfigurable control law with linear programming based control allocation [25], robust PI servomechanism and quadratic programming-based control allocation [26], a direct adaptive neural network based controller [27], trajectory linearization [28, 29], sliding mode control [30] which all met with some degree of success and offered improvements in design time and fault tolerance when compared to baseline system.

## 2. The Role of Integrated Vehicle Health Management Systems

Many adaptive guidance and control technologies rely to some extent upon information regarding the failures or damage to the vehicle. This is particularly true of indirect adaptive control schemes where the model parameters must be estimated in order to compute the solution to an on-line control design problem. Direct adaptive schemes rely less on this feature because they generally adapt based only on tracking error behavior; however, the combination of direct and indirect adaptive techniques may lead to better performance than could be achieved by using either technique alone. Research combining the two approaches with application to space access has been sparse; however, one effort is documented in [31].

The development of adaptive guidance and control technologies has outpaced the development of IVHM systems to some extent. Part of the reason for this is that the concept of IVHM extends to monitoring all parts of the vehicle for many different purposes and the term is often interpreted parochially by different engineering disciplines. Some communities interpret IVHM as built-in test or diagnostic systems designed for use by ground maintenance personnel, while the flight control community views IVHM as a necessary function that will alert reconfigurable guidance and control systems to the presence of failures or damage to the vehicle. For the purposes of this manuscript we will discuss IVHM from the latter point of view.

One of the principal uses of IVHM information concerns the health of the aerodynamic control surfaces. Control surfaces on autonomous systems may be powered by electric, hydraulic or pneumatic actuators through mechanical drives which ultimately move the surface. Such an arrangement can fail or degrade in multiple ways:

- Loss or reduction of power leading to reduced actuator bandwidth, rate or position limits
- Locked actuator, servovalve failure or drive mechanism preventing surface movement
- Faulty command to actuator resulting in a locked surface
- Loss of power or mechanism failure resulting in a floating surface incapable of resisting aerodynamic force
- Damage to control surface resulting in loss of effectiveness

In order to provide useful information to an IAG&C system, any of the above anomalies must be translated into updated estimates of control effectiveness, actuator dynamic model parameters, as well as rate and position limits. The translation of IVHM sensor measurements into information useful for control reconfiguration is a challenge that has yet to be addressed. It should be noted that floating surfaces and damage resulting in a loss of control effectiveness are two instances where IVHM and on-line system identification algorithms may be able to complement one another. Static on-line system identification methods [1, 32, 33, 34, 35] may be capable of providing information to the IVHM system that can improve diagnostic health information.

Knowledge of the degradation of control surface performance is of high importance to IAG&C systems particularly for unpowered flight. For the ascent flight phase, anomalies in engine performance are important as well. Non-catastrophic engine anomalies include power-pack-out on multi-engine liquid fueled boost vehicles due to turbo pump failures, off-nominal engine performance or thrust vectoring actuator failures. It would be desirable for IVHM systems to identify such failures and translate the effects of the failures to the IAG&C system. Thrust vectoring actuators, including nozzle gimbal actuators or differential throttles, are critical in the early phases of ascent flight because the aerodynamic actuators are not effective due to a lack of dynamic pressure. The task of stabilizing and guiding what amounts to an accelerating inverted pendulum therefore falls to the thrust vectoring system. The control effectiveness, rate and position limits as well as the system dynamics of the thrust vectoring system are highly desirable quantities that should be gleaned from IVHM sensor measurements. During exo-atmospheric flight, space access vehicles may rely on reaction control jets, reaction wheels, torque tubes or a combination of these effectors in order to generate forces and moments on the body. Again, the ability to extract information from IVHM sensors for use by IAG&C systems is in its infancy and in the near-term, control designers may be forced to rely upon on-line system identification to provide this information. Some launch vehicle designs, such as the X-33, were configured to tolerate the loss of one or more turbo-pumps past some critical point in the boost phase by maintaining the ability to vector the thrust via differential throttles, albeit at reduced levels of effectiveness. Thus, vehicles can be designed in such a way as to avoid single-point failures and should be designed to take advantage of advances in IAG&C technology in order to maximize system survivability. For example, a simple way of improving survivability is to split large single control surfaces into multiple control surfaces driven by separate actuators and mechanical drives; however, since weight is at such a premium on launch vehicles, the enhanced survivability must be balanced with launch costs based on the application.

Another useful category of IVHM information for the flight control designer is the vehicle mass properties. During ascent flight, the mass properties of launch vehicles change dramatically. Accurate knowledge of mass, center-of-gravity and moments of inertia improves the performance of not only IAG&C algorithms but also model based baseline flight control laws like dynamic inversion. For liquid fueled rockets, estimation of mass properties based on intial conditions and flow rate measurements may be possible and would be desirable information to feed to IAG&C systems.

Among most challenging parameters to estimate from IVHM data are trajectory constraints for failed or damaged vehicles. Constraints such as dynamic pressure, load factor, angle-of-attack, heat load and heating rates specified for the nominal vehicle may change as a result of failures or damage to the vehicle. Goals for future IVHM capabilities include the ability to diagnose and assess the health of the airframe structure and thermal protection system[36]; however, translating IVHM sensor measurements into revised constraints that can be used by trajectory retargeting or reshaping systems is an extremely challenging problem.

It would also be desirable for future IVHM systems to provide instantaneous outer-mold line estimates for launch and reentry vehicles. By using optical or structurally embedded sensors, it may be possible to estimate how damage has affected the aerodynamic shape of the vehicle. Damage that affects the vehicle outer mold line is a particularly difficult challenge for trajectory reshaping algorithms because the aerodynamic effects of the damage have to be estimated over a wide range of flight conditions, not just at the current flight condition. This is because trajectory reshaping is inherently a forward-looking process that requires knowledge of the dynamic model of the system as well as the constraints on the states and controls. IVHM based estimates of the vehicle outer-mold-line can be coupled with fast aerodynamic prediction codes such as DATCOM[37] in order to provide rough but representative aerodynamic models of damaged vehicles at flight conditions yet to be encountered. Two nascent approaches to solving this problem have been published in the literature[38, 39].

## 3. Control Allocation

Control allocation is a term that has been used to describe methods that mix or blend control effectors in order to achieve some desired result. As will be seen, control allocation has a pervasive role in fault-tolerant autonomous guidance, control and trajectory generation, in spite of the fact that most methods were intended only to simplify the blending of control effectors for inner-loop flight control. Most early work focused on over-actuated air vehicles. Over-actuating a flight vehicle provides a certain amount of redundancy for the flight control system and potentially allows recovery from control effector failure conditions. In cases where such redundancy exists, control allocation algorithms are useful for to computing a unique solution to the over-actuated control mixing problem. Control allocators compute commands that are applied to the actuators so that a specified set of forces or moments are generated by the control effectors. In the literature, control allocation problems are often formulated as optimization problems so that all of the available degrees of freedom can be utilized and, when sufficient control power exists, secondary objectives such as drag minimization can be achieved.

To illustrate the function of a control allocator, consider a conventional aircraft that utilizes an elevator for pitch control, ailerons for roll control, and a rudder for yaw control. The control mixing on historic aircraft was accomplished by ganging or direct mechanical linkages such as cable and pulley arrangements as shown in Figure 1. As flight vehicle technology advanced, ganging has been accomplished by flight computers whose widespread use eventually let to the use of greater numbers and wider varieties of control effectors for flight vehicles. From the perspective of reconfigurable control, the ability to remix the control effectors online following a failure now exists and modern control allocation methods have played major roles in recent reconfigurable flight control designs[40, 35, 11]. In some cases, certain control effectors may be able to exert significant influence upon multiple axes. Due to this over-actuation and coupling of control surface effects, the problem of how to appropriately mix numerous control surfaces together to achieve a desired result becomes nontrivial. In addition, nonlinearities such as rate and position limits of the control surfaces must be considered in order to achieve a viable solution to the problem.

Some of the simplest control allocation techniques are explicit ganging, pseudo inverse, and daisy chaining[41]. Unfortunately, ganging and pseudo inverse methods suffer from difficulties in guaranteeing that rate and position limits will be respected and the daisy chaining method can return non-unique solutions that are dependent upon the order in which surfaces saturate. Another control allocation method, called direct allocation [42], finds the control vector that results in the best approximation of the command vector in a given direction. Unconstrained least squares control allocation methods, that account for rate and position limits, through the use of penalty functions, have also been developed [43]. One of the first instances of linear programming based control allocators was from Paradiso [44, 45]. In this work, Paradiso developed an selection procedure for determining actuator positions that was based on linear programming and limited actuator authority. More recently, the control allocation paradigm has been posed as a constrained optimization problem [40]. In this work, the control allocation problem was split into two subproblems. The first was the error minimization part, which attempts to find the control vector, such that the control effector induced moments or accelerations match the desired moments or accelerations. If multiple solutions exist to the error minimization problem, a second optimization problem is posed that is designed to find a unique solution by driving the control effectors to some preferred position that accomplishes some secondary objective. Quadratic programming has also been used in the the solution of control allocation problem [46]. An excellent paper discussing many optimization based control allocation methods has been published by Bodson [47] which also includes a linear programming formulation knows as mixed optimization that combines error and secondary objective minimization as a cost criteria.

The above referenced methodologies are applicable to linear control allocation problems of the form:

$$\mathbf{B}\delta = \mathbf{d_{des}} \tag{1}$$

subject to

$$\begin{aligned} \delta_{min} \leq \delta \leq \delta_{max} \\ |\dot{\delta}| \leq |\dot{\delta}_{max}| \end{aligned} \tag{2}$$

where $\mathbf{B} \in \mathbb{R}^{\mathbf{m}\times\mathbf{n}}$ is a control effectiveness matrix, the lower and upper position limits are defined by $\delta_{min} \in \mathbb{R}^n$ and $\delta_{max} \in \mathbb{R}^n$, respectively, $\dot{\delta} \in \mathbb{R}^n$ are the control rates, $\dot{\delta}_{max} \in \mathbb{R}^n$ are the maximum control rates, $\mathbf{d_{des}}$ are the desired moments or accelerations (typically for inner-loop control laws, $\mathbf{d_{des}} \in \mathbb{R}^3$), $n$ is the number of control effectors, and $m$ is the number of axes to control. Equation 4

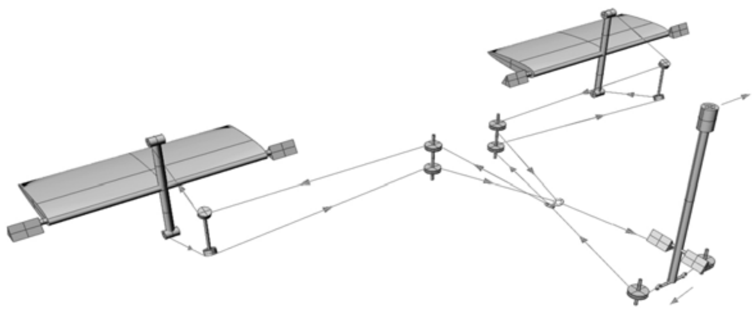

Figure 1. Mechanical ganging of ailerons on historical aircraft

provides the position and rate limits for the control effectors. In a digital computer implementation, the rate limits are converted to effective position limits. It is also noteworthy that these methods implicitly assume that the actuator dynamics negligible and that the actuators respond instantaneously to the commands from the control allocator.

Recent work has sought to relax the assumptions of linearity between the control effector positions and the control variables. The linear control allocation problem has been extended to an affine problem [48] to account for nonlinearities in the moment-deflection curves; however, this method is applicable to systems of the form:

$$\sum_{j=1}^{n} g_i(\delta_j) = d_{i_{des}}, i = 1 \ldots m \tag{3}$$

subject to

$$\begin{array}{c} \delta_{min} \leq \delta \leq \delta_{max} \\ \dot{\delta} \leq \dot{\delta}_{max} \end{array} \tag{4}$$

where $g_i(\delta_j)$ are monotonic functions of control effector positions. The monotonic restriction means that there can be no slope reversals or changes in the signs of the flight vehicle control derivatives at any flight condition. Additional research by Bolender and Doman [49] has produced a nonlinear control allocation methodology that relaxes the monotonicity restriction on the functions; however, the functions must be separable, i.e. no interactions between control effectors. The problem of solving control allocation problems for cases where interactions between control effectors exist, such as a case where one effector is downstream of another, is still an open research problem. The most direct method of attacking this problem is through the use of nonlinear programming; however, the application of this technique to flight critical systems is hampered by a lack of convergence guarantees.

Recent research in the area has also led to control allocation methods that allow the effects of actuator dynamics to be addressed [50, 51, 52]. The method of Reference [50] is particularly appealing because it can be used to post process the outputs of any control allocator to compensate for the effects of actuator dynamics. The method is however, dependent upon a priori knowledge or instantaneous estimates of the actuator dynamics. While static control allocation techniques have been successfully applied to numerous flight vehicles and flight vehicle models, problems can arise when attempting to allocate effectors whose bandwidth nears that of the rigid body aircraft. The use of constrained control allocation techniques with band limited effectors leads to an effective reduction in effector rate limits which can be eliminated by post processing allocator commands by scaling. Also, blending a suite of control effectors with widely varying bandwidths such as engines and aerodynamic surfaces can be problematic. The post-processing procedure can be used to mitigate such problems and can also be used to compensate for changes in actuator dynamics that result from actuator power degradation as discussed in the section on IVHM.

### 3.1. Role of Control Allocation in System Identification

System identification techniques require input and output excitation in order to obtain reliable measurement based estimates. In order to identify elements of the control effectiveness matrix, each control effector must be active at all times. Furthermore, each effector must be moving independently so that there is little to no correlation between the movement of one control effector and another. Decorrelated control deflections are necessary to obtain a well conditioned regressor matrix, for system identification[32, 35]. The addition of small zero-mean signals to the actuator commands, sometimes called dithering, can be used to provide an acceptable level of input excitation. Unfortunately this simple approach results in degraded vehicle response since in general $\mathbf{B}(\delta + \delta_{\mathbf{dither}}) \neq \mathbf{d_{des}}$. One solution to this problem is to provide a dithering signal that lies in the null space of $\mathbf{B}$, i.e. $\mathbf{B}\delta_{\mathbf{dither}} = \mathbf{0}$ so that $\mathbf{B}(\delta + \delta_{\mathbf{dither}}) = \mathbf{d_{des}}$. The construction and application of such a dithering signal is called null-space signal injection.

Many of the optimization based control allocation methodologies allow for the use of a preference vector $\delta_p$ that aids in defining a problem that has a unique solution when the principal control objective $\mathbf{B}\delta = \mathbf{d_{des}}$ can be achieve in multiple ways. In such cases the allocation algorithms will attempt to minimize the difference between the actual control deflections and $\delta_p$. Often, the preference vector is taken to be a pseudo-inverse solution so that

$$\delta_p = -\mathbf{c} + \mathbf{W}^{-1}\mathbf{B}^T(\mathbf{B}\mathbf{W}^{-1}\mathbf{B}^T)^{-1}[\mathbf{d}_{des} + \mathbf{B}\mathbf{c}] \qquad (5)$$

where $\mathbf{c}$ is an offset vector and $\mathbf{W}$ is a diagonal weighting matrix of the form

$$\mathbf{W} = \mathrm{diag}\left[W_{\delta_{RF}}\, W_{\delta_{LF}}\, W_{\delta_{RR}}\, W_{\delta_{LR}}\, W_{\delta_{SB}}\, W_{\delta_{BF}}\right] \qquad (6)$$

The elements of the offset vector $\mathbf{c}$ are all zero except for the elements corresponding to locked control surfaces. If a control effector is locked, then the corresponding entry in $\mathbf{c}$ is set to the negative of the locked location. Using this preference vector allows one to analytically represent the control allocator in a robustness analysis that is valid as long as no single axis is saturated and the commanded accelerations are feasible.

This preference vector can also be used to implement null space signal injection to aid in system identification. This can be accomplished by randomly perturbing the weighting matrix in Equation 5 at each time step according to:

$$\mathbf{W} = \tilde{\mathbf{W}}\mathbf{W_r} \qquad \mathbf{W_r} = \mathrm{diag}(\mathbf{10^{v_1}}, \mathbf{10^{v_2}} \cdots \mathbf{10^{v_m}}) \qquad (7)$$

and $\mathbf{v}$ is a vector of uniformly distributed random variables between -1 and 1. The matrix $\tilde{\mathbf{W}}$ is a nominal diagonal weighting matrix used for scaling purposes to equally distribute commands. Thus, the preference vector will be driven toward a randomly weighted least squares solution to the control allocation problem that does not account for rate and position constraints. This approach ensures that the control effectors are decorrelated and active without degrading the vehicle response and also avoids the explicit calculation of the null space of $\mathbf{B}$.

### 3.2. Role of Control Allocation in Outer Loops

Constrained control allocators can play a role in preserving stability margins of outer guidance loops when axis saturation occurs. While control effector saturation is generally undesirable, it has little to no consequence as long as additional control power is available from redundant effectors. When all control power is depleted in the pitch, roll or yaw axes, inner loops that regulate body axis angular rates or linear accelerations effectively become open, a condition which is undesirable under all circumstances and one that must be avoided for open-loop unstable systems. Additionally, frequency separation arguments used to justify the independent design of inner and outer loops in a sequential loop closure architecture may no longer be valid when insufficient control power precludes the generation of the desired moment or acceleration commands. Reducing the demands on the inner loop by changing outer loop design parameters is one way of mitigating axis saturation problems. In [11] the bandwidth of the explicit models used to drive an inner loop model following system were reduced in response to axis saturation. Axis saturation can easily be predicted or detected by most constrained control allocation methods. The bandwidths of the explicit models were reduced according to simple rules that reduced the bandwidths until axis saturation ceased and then increased the bandwidths toward the nominal values in order to achieve performance as close to nominal as possible. The instantaneous values of the explicit model parameters were used to schedule outer-loop gains in order to preserve stability margins.

The detection or prediction of axis saturation by control allocators may also be used in conjunction with pseudo-control hedging methods [53, 27] that are designed to enforce certain assumptions that prevent direct adaptive control schemes from losing stability. Pseudo-control hedging is a method of “hiding” errors caused by control power limitations or other known limitations such as time delay from adaptation laws that attempt to compensate for modeling errors. It has been observed that direct adaptive schemes can mistakenly interpret tracking errors caused by axis saturation as modeling error which can lead to controller instability because the adaptive control signals grow thereby driving the actuator commands further into saturation.

### 3.3. Role of Control Allocation in Trajectory Reshaping

Due to the forward-looking nature of trajectory reshaping methods, vehicle constraints and aerodynamic properties must be estimated at flight conditions beyond the point at which a failure is detected. This requirement contrasts sharply with that of inner-loop reconfigurable control where one only requires a snapshot of the current model parameters that can either be obtained through on-line system identification or directly from IVHM/FDI. While the problem of estimating the effects of locked or floating effector failures over the flight envelope is tractable due to invariance of the aerodynamic database, techniques for estimating the effects of damage over the flight envelope are nascent. There have been some recent efforts to develop algorithms for predicting the effects of damage over the flight envelope that will require an extensive amount of information from an IVHM system[39, 38]. These prediction methods will require outer-mold-line information, presumably obtained from an advanced IVHM system, to drive fast aerodynamic prediction codes such as DATCOM[37] that can generate estimates of aerodynamic coefficients, which can be blended with temporally local estimates from system identification algorithms. The degree of difficulty in obtaining accurate estimates depends upon the flight condition at which the damage occurs. For example, if damage occurs in the hypersonic flight regime, one does not expect to see large changes in the aerodynamic coefficients until the aircraft approaches the transonic flight regime where the aerodynamic characteristics are often highly sensitive to changes in Mach number.

The computation of reshaped trajectories online requires that two major issues be solved. The first is that flight certifiable algorithms must be developed so that trajectories can be computed on-line and the second is that methods must be developed that allow the effects of failures or damage on the vehicle to be predicted over the flight envelope to be explored by the trajectory reshaping algorithms.

The varying nature of reduced order aerodynamic models and constraints, will now be illustrated. It is assumed that the sideslip angle $\beta = 0$ and that symmetric flight conditions exist. Therefore, the lateral directional wing-body forces and moments will be assumed to be zero.

To begin the analysis, the wing-body pitching moment coefficient of the vehicle is calculated at each data point $(j,i)$ in a grid spanning the regions of interest in the aerodynamic database giving

$$C_{m_{oj,i}} = f\left(M_j, \alpha_i\right) \tag{8}$$

where $C_{m_{oj,i}}$ is the base pitching moment coefficient at the $j^{th}$ Mach ($M_j$) and $i^{th}$ angle of attack ($\alpha_i$) data point. Since only longitudinal motion is considered here, it is assumed that $C_{l_{oj,i}}(M_j,\alpha_i) = 0$ and $C_{n_{oj,i}}(M_j,\alpha_i) = 0$, where $C_{l_{oj,i}}(M_j,\alpha_i)$, $C_{n_{oj,i}}(M_j,\alpha_i)$ are the base rolling and yawing moment coefficients at the $(j,i)$ data point, respectively. Now that the wing-body pitching moment has been computed, a control allocation scheme is used to provide the control effector settings, $\delta_{j,i} \in \mathbb{R}^m$ (m = number of control effectors), that rotationally trim the vehicle. Hence, at each point in the Mach-$\alpha$ envelope, it is desired to find $\delta_{j,i}$ such that

$$\begin{pmatrix} C_{l_{\delta_{j,i}}}(M_j,\alpha_i,\delta_{j,i}) \\ C_{m_{\delta_{j,i}}}(M_j,\alpha_i,\delta_{j,i}) \\ C_{n_{\delta_{j,i}}}(M_j,\alpha_i,\delta_{j,i}) \end{pmatrix} = \begin{pmatrix} 0 \\ -C_{m_{oj,i}}(M_j,\alpha_i) \\ 0 \end{pmatrix} \tag{9}$$

where $C_{l_{\delta_{j,i}}}(M_j,\alpha_i,\delta_{j,i})$, $C_{m_{\delta_{j,i}}}(M_j,\alpha_i,\delta_{j,i})$, and $C_{n_{\delta_{j,i}}}(M_j,\alpha_i,\delta_{j,i})$ are the rolling, pitching, and yawing moment coefficients produced by the control effectors.

All control effectors are position limited so that $\underline{\delta} \leq \delta_{j,i} \leq \overline{\delta}$ where $\underline{\delta}$ and $\overline{\delta}$ are vectors whose elements correspond to the lower and upper limits of the $k^{th}$ control surface. Without loss of generality, locked control effectors are characterized by $\underline{\delta}_k = \overline{\delta}_k$, while floating control effectors are characterized by their lack of moment generating capability, i.e., $C_{l_{\delta_{j,i}}} = C_{m_{\delta_{j,i}}} = C_{n_{\delta_{j,i}}} = 0$. We utilize a piecewise linear constrained control allocator [49] to find the appropriate value of $\delta_{j,i}$ which satisfies Equation 9. Let $\delta^*_{j,i}$ denote a solution to Equation 9. If $\delta^*_{j,i}$ can be found such that Equation 9 is satisfied, then sufficient control power exists to longitudinally trim the vehicle. On the other hand, if Equation 9 is not satisfied, then a deficiency exists. By performing this test at each Mach-$\alpha$ point, a rotational trim deficiency map can be constructed. This map indicates where the vehicle is longitudinally trimmable; hence, the map displays trim information for all Mach numbers and angles of attack in the aerodynamic database. In particular, when a point in the deficiency map is zero, then that point is declared longitudinally trimmable; when there is a nonzero value, then a deficiency exists and that point is not trimmable. Thus, from this information, one can determine regions of trimmable angle of attack, the boundaries of which, constitute constraints that must be communicated to trajectory reshaping algorithms.

Similar to generating the trim deficiency map, trim force coefficient maps can be created. These maps provide the lift and drag at every operating condition for which a model is available. The lift and drag can be computed at each operating point by substituting the solution to Equation 9, $\delta^*_{j,i}$, into the aerodynamic database and calculating the trim lift and drag coefficients. The total lift and drag coefficients are given by the sum of the wing-body and control surface coefficients for a given Mach-$\alpha$ pair and corresponding $\delta^*_{j,i}$:

$$\begin{aligned} C_L\left(M_j,\alpha_i\right) &= C_{L_o}\left(M_j,\alpha_i\right) + C_{L_{\delta^*_{j,i}}}\left(M_j,\alpha_i,\delta^*_{j,i}\right) \\ C_D\left(M_j,\alpha_i\right) &= C_{D_o}\left(M_j,\alpha_i\right) + C_{D_{\delta^*_{j,i}}}\left(M_j,\alpha_i,\delta^*_{j,i}\right) \end{aligned} \tag{10}$$

where $C_L\left(M_j,\alpha_i\right)$ and $C_D\left(M_j,\alpha_i\right)$ are the total lift and drag coefficients, $C_{L_o}\left(M_j,\alpha_i\right)$ represents the wing-body lift coefficient, $C_{D_o}\left(M_j,\alpha_i\right)$ represents the sum of the wing-body induced and parasitic drag coefficients, and $C_{L_{\delta^*_{j,i}}}\left(M_j,\alpha_i,\delta^*_{j,i}\right), C_{D_{\delta^*_{j,i}}}\left(M_j,\alpha_i,\delta^*_{j,i}\right)$ are the sum of the lift and drag coefficients produced by the control effectors, respectively.

This method yields the control deficiency map as well as the lift and drag maps. Each map is valid for all operating conditions for which a model is available. Such information is suitable for use with trajectory reshaping algorithms that are based on 3 degree-of-freedom vehicle models as a way of incorporating 6 DOF effects into a 3 DOF model.

As an example we consider a reentry vehicle with 8 control effectors. The method described above is used to compare the trim maps and trim force coefficients of the nominal vehicle to those of a failed vehicle. The nominal vehicle is capable of trimming over the entire range of Mach number and angle-of-attack of interest; however when both body flaps fail a $26^o$, the trimmable region shrinks significantly as shown in Figure 2. This figure immediately portrays the feasible range of angle of attack (angle of attack values for which the trim deficiency map is zero). For a trajectory which would span the entire Mach range shown here, it can be seen that the range of feasible angle of attack is much smaller than the range of the nominal case. In fact, the feasible region of angle of attack and Mach number reduces to a corridor on the Mach-$\alpha$ grid.

Now, the trim force coefficients will be investigated. Figures 3 and 4 illustrate the effect of the failure upon the drag and lift forces. One can see that the failure induced constraints, be it trimmable angle of attack, drag, or lift are not constant from one flight condition to another. This information would be used by a trajectory reshaping algorithm to compute a new trajectory to finish the mission. Coupling the range of trimmable angle of attack with drag and lift maps for a full-envelope of operating conditions provides a trajectory reshaping algorithm the information required to compute a feasible trajectory, if possible, throughout the remaining flight regime, given the vehicle's limitations.

Finally we note that work is also currently underway that is exploring the feasibility of solving trajectory reshaping problems by directly including 6 DOF models and reconfigurable flight control algorithms in the propagation of the equations of motion used in the trajectory optimization process [54, 55]; however, at the present time, the feasibility of the procedure is still in question. Direct use of the the 6 DOF and flight control models would eliminate the need to compute trim maps and estimate the effects of control failures upon trim lift and drag coefficients.

## 4. Verification and Validation

Advanced guidance, control and trajectory reshaping algorithms described present significant challenges for current verification and validation (V&V) procedures. Emphasis has been placed on developing and fielding autonomous systems not only in the area of space access but also in the area of unmanned air vehicles. The role of the adaptive human pilot is being replaced with control laws that can adapt, learn, optimize, predict, reason, cooperate, and make decisions [56]. Each of these attributes challenges current V&V processes and tools as the advanced algorithms may be nondeterministic. Thus, flight certification of these advanced control laws for use in aircraft is difficult.

V&V procedures for such methods significantly lag the development of the advanced control algorithms themselves, nevertheless, some techniques have emerged out of the necessity to test and flight demonstrate advanced methods. For example, empirical stability margin tests have been developed [57]. With this technique, a frequency sweep input is inserted into each axis of the control law and the frequency response of the output signal to the error signal is measured. This frequency response represents the open-loop transfer function, for a given axis. The stability margins are extracted from high fidelity simulations or test and over a range of flight conditions. In addition, researchers have inserted gain and delay perturbations into the simulation models and adjusted their effect to determine when the system becomes neutrally stable. This time consuming technique provides measures of robustness for nonlinear and adaptive systems that are related to gain and phase margins used to evaluate conventional systems.

There exists a great need for advances in V&V procedures. Some approaches to advanced V&V for flight critical systems include translation of requirements into design specifications such as model-based design environments and advanced design techniques, which take into account the need to perform V&V [58, 59]. Utilizing algorithms that possess guaranteed convergence properties is one step toward designing control laws that have the potential to pass a V&V process for a flight critical system. Also, advanced V&V techniques may include automating some of the work performed by an engineer, such as, adjusting the gain and delay uncertainties in feedback loops.

In the paper by Cao [60], et.al., the robustness of two adaptive control approaches for a SISO LTI system with an output disturbance with a high gain controller was investigated. A standard model reference adaptive controller and an $\mathscr{L}_1$ adaptive controller were considered. For the model reference controller, it was shown that the phase margin is affected by the adaptation gain. As the adaptation gain increases, the crossover frequency increases, but the phase margin is reduced. Consequently, the time delay margin (the ratio of phase margin to crossover frequency) is reduced. For the $\mathscr{L}_1$ adaptive controller, the phase margin is independent of the adaptation gain because the structure of the open-loop plant changes due to the presence of an additional estimation block in the system. However, when a time delay in the plant input is considered, the open-loop plant is explicitly dependent upon the adaptation gain, thus the time delay margin is dependent upon the adaptation gain. Yet, the definition of the time-delay margin as given above no longer holds. An analysis of the open-loop transfer function with a time delay in the plant input shows

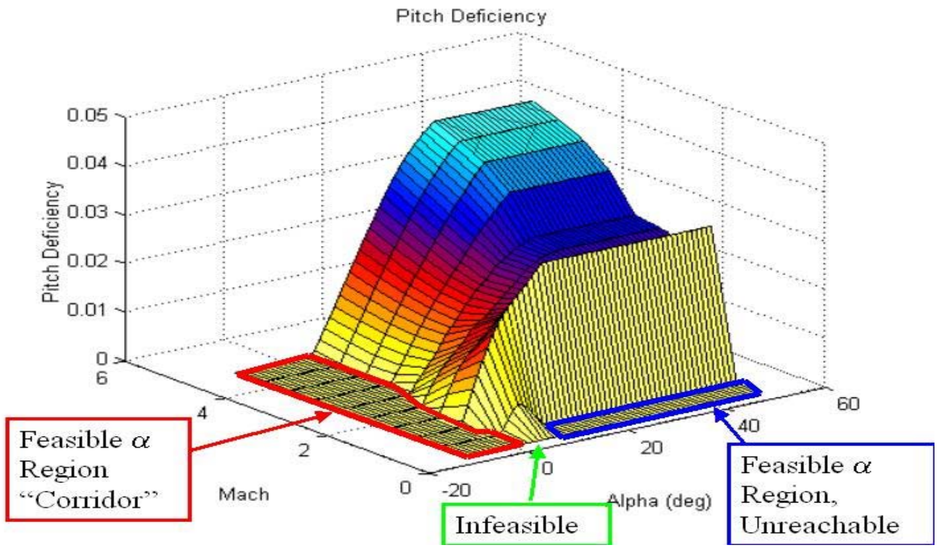


Figure 2. Pitch Deficiency: Feasible $\alpha$ Corridor And Unreachable Regions.

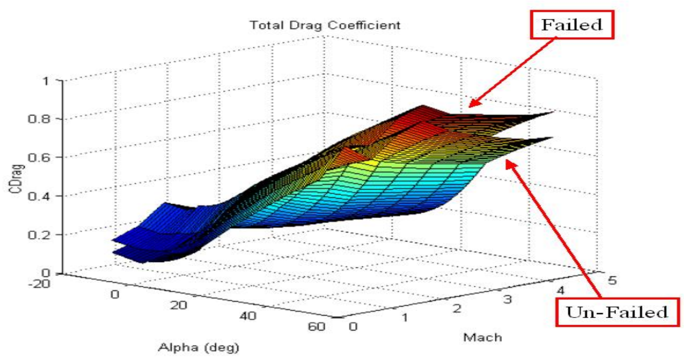


Figure 3. Drag Coefficient For Failed And Un-Failed Configurations.

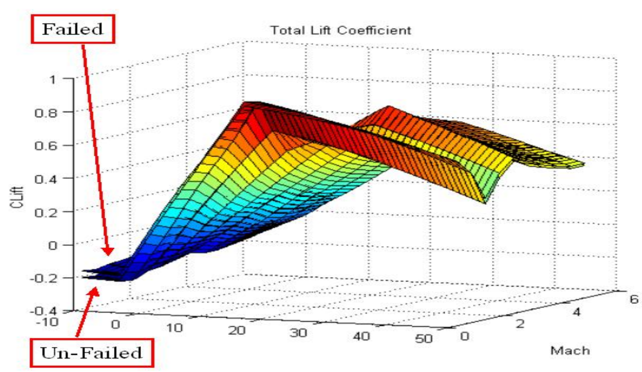


Figure 4. Lift Coefficient For Failed And Un-Failed Configurations.

that in the limit that the adaptation gain tends to infinity, the time delay margin approaches a non-zero value, thus ensuring robustness. The authors conclude that a high gain can improve robustness of the system when the high gain is "internal to the controller computation block."

Other approaches tailor the algorithms themselves so that they can pass a V&V process. While this may limit the capabilities of the methods, advanced methods will fail to find application to flight vehicles if they cannot guarantee a solution in a guidance or control computation frame. This is particularly true in the area of trajectory reshaping or retargeting. On-line trajectory optimization involves the solution of two-point boundary value problems which can be notoriously difficult and time consuming to solve. Guaranteeing the solution to a two point boundary value problem in a real-time flight critical system is not currently possible. One successful alternative [11] that has been flight demonstrated, is to form a trajectory database by solving large numbers of two-point boundary value problems offline and storing them in a compact form suitable for use on a flight computer. The key to making such an approach work is not to design a trajectory for every possible combination of failures. In this case, a trajectory database was created an unpowered flight vehicle in the approach and landing phase. When some combination of control effectors fail, a reconfigurable inner-loop control law maintained control of the rotational degrees of freedom; however, lift and drag perturbations resulted which can significantly influence the trajectory. The *effect* of a control failure upon the lift and drag can be calculated because the aerodynamic database does not change as a result of a locked or floating control surface failure. The perturbations in lift and drag are then used as indices with which a modified trajectory is selected. The offline computation of trajectories therefore involves solving two point boundary value problems over a range of perturbations in lift and drag and not over a range of specific control effector failures. Because of the deterministic nature of this approach, the V&V of the trajectory retargeting algorithm is simplified.

A less conservative approach was adopted for a hardware-in-the-loop test of a trajectory reshaping method for terminal area energy management and approach and landing for the X-37 [61]. In this case the trajectories were specified by just six decision variable parameters. Computation of the solutions to the trajectory reshaping problems were computed in real-time using the X-37 flight computers using weighed pseudo-inverse methods for a large number of control surface failures. While the method requires less storage and is more capable than a trajectory database approach, V&V of such a system is more challenging due to a lack of guaranteed convergence. More capable and complex trajectory optimization algorithms have been developed [62, 63, 64, 39, 38, 54] but currently have little chance of passing a V&V process for a flight vehicle for the same reason. For the foreseeable future, any trajectory optimization algorithm that does not guarantee convergence must be backed up by reversion modes that return some feasible trajectory that can be flown in the event that convergence is not achieved.

## 5. Control Challenges for Scramjet Powered Vehicles

Ongoing research is exploring the challenges of controlling air-breathing hypersonic vehicles such as that shown in Figure 5. Subscale flight vehicles such as the X-43 have flown and demonstrated the ability to develop positive net thrust at hypersonic speeds [65]. In spite of the success of these subscale tests, the development of full scale vehicles is dependent upon advances in materials and the ability to control of an integrated airframe propulsion system. Full scale vehicles will be more difficult to control due to more significant interactions between the aerodynamics, propulsion system, and structural dynamics.

A representative cross section of a generic air-breathing hypersonic vehicle is given in Figure 6. One of the first models to capture the salient features of this class of vehicle was based on first principles and was developed by Chavez and Schmidt [66]. More recently a model developed by Bolender and Doman [67] has been developed that relaxes a number of simplifying assumptions made in the Chavez and Schmidt model. These integrated, control oriented models have predicted that full scale aircraft will be characteristically unstable in pitch and will exhibit non-minimum phase behavior between many important inputs and outputs. The model of [67] accounts for mass-flow spillage effects that occur as a result of the engine operating in off-design conditions when the bow shock does not impinge on the inlet lip. Off-design conditions will commonly be encountered as the aircraft structure oscillates because the bow shock angle will change as the structure deforms. Operation under off-design conditions affects the aerodynamic forces and moments, as well as the thrust. The nonlinear vehicle model makes use of oblique shock theory and Prandtl-Meyer flow theory (i.e., gas dynamics) to calculate the aerodynamic forces. Reflected shocks are modeled in the scramjet diffuser, while the nozzle is assumed to be isentropic. A fuel flow model is used in the combustor section which is modeled using Rayleigh flow (1D compressible flow with heat addition.) Because the aircraft structure is lightweight due to the amount of fuel that is carried on-board, the structural dynamics for this class of vehicle play an important role. Typically, the frequency of the fuselage first bending mode, when the aircraft is fully loaded, is low enough to interact with the flight control system. As the aircraft flies its mission, the reduction of the aircraft's weight will cause the frequencies to increase; however, this is offset a small amount (2-3%) by the aerodynamic heating that propagates into the load bearing vehicle structure [68, 69]. One of the most significant issues associated with the vehicle structural dynamics is the that the oscillating forward fuselage changes the pressure distribution over the forebody of the aircraft which creates a number of undesirable natural loop closures to occur. The fuselage deflection is dependent upon the flight condition (Mach number, altitude, and angle-of-attack) since this determines the pressure distribution on the vehicle. Furthermore, the deflection of the forward fuselage changes the apparent turn angle of the flow. Therefore, during unsteady flight, the resulting changes in the pressure distribution over the aircraft are realized downstream as perturbations in the thrust, lift, drag and pitching moment. In addition unsteady aerodynamic effects resulting from the oscillating structure influence the forces and moments on the vehicle as a result of local pointwise pressure variations. Methods [70, 71] to enhance quasi-steady aerodynamic models by using nonlinear piston theory to account for these unsteady aerodynamic effects without incurring a large computational burden are currently being incorporated into control oriented models for study.

Recent work in the control of scramjet powered hypersonic vehicles has proceeded along two fronts: control synthesis and vehicle configuration design for control. The first approach involves determining an acceptable control methodology that can extract a reasonable level of maneuvering performance from an unstable non-minimum phase aircraft configuration [72]. A pseudo dynamic inversion controller was developed that decouples the system but leaves the right-half plane zeros intact in order to avoid cancellation of unstable zeros with unstable poles. The second approach [73] involves determining how to modify the vehicle configuration to make it more amenable to the application of control technology. One of the principal problems with tail controlled hypersonic vehicles is the presence of low frequency, non-minimum phase transmission zeros that limits the performance of any feedback control method. The primary cause of this phenomenon arises because when the vehicle is trimmed, a substantial portion of the total lift comes from the elevons. When a change in lift is desired, the elevons must dump lift in order to generate a nose-up pitching moment that, over time, leads to an increase in lift as a result of increased forebody angle of attack. This phenomenon is directly responsible for the low frequency unstable zeros and also puts the vehicle center of rotation several feet in front of the nose of the vehicle. By coupling the elevator and canard via a simple interconnect gain, it was found that substantial increases in the the unstable zero frequencies could be achieved. The result is that with a simple configuration change, one may substantially improve the ability of any control technique to produce an acceptable flight path speed of response. Other factors such as low excess power and limited control power are also being considered in the model and control design and ultimately limit speed of response; however, a major fundamental control limitation has effectively been eliminated by a simple configuration change. This case study is an example of how the work of flight control engineers can interject control requirements to vehicle designers early in the design process. Because of the multi-disciplinary nature of scramjet vehicle design, this type of interaction will be critical to achieving successful full scale vehicle designs.

## 6. CONCLUSIONS

Strides in the development of integrated adaptive guidance, control and trajectory reshaping algorithms for space access vehicles have largely outpaced verification & validation and integrated vehicle health monitoring systems. Aside from further developments in V&V and IVHM, algorithms to be implemented in the near term should to be tailored to pass current V&V procedures and may have to rely on minimal information from IVHM systems. Multidisciplinary modeling for control is important to ensure that systems are designed to take advantage of capabilities offered by new control technologies. Advanced algorithm capabilities and limitations must be made clear to vehicle designers early in the design process in order to ensure that new vehicle designs can fully benefit from the latest and most promising fault tolerant control technologies.

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Figure 5. Artist's Concept of an Air-breathing Hypersonic Vehicle

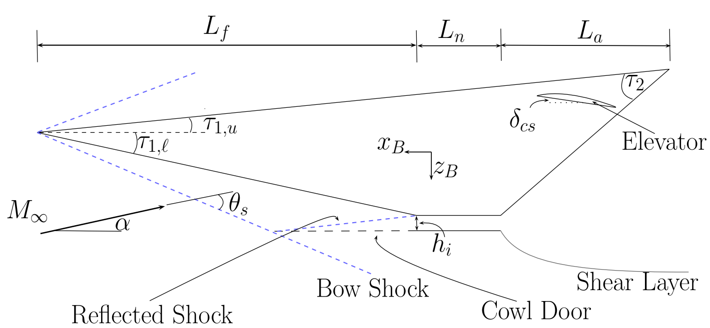


Figure 6. Hypersonic Vehicle Geometry

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